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The Vulnerability/Lethality Taxonomy as a General Analytical Procedure

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The Vulnerability/Lethality Taxonomy as a General Analytical Procedure

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Abstract

In this report, the vulnerability/lethality (V/L) taxonomy originally presented by Deitz and reformulated by Klopcic, Starks, and Walbert is shown to contain a general analytical procedure, herein referred to as the KSW process, which is applicable to a broad class of problems that meet the criteria for its use. When used as a general analytical procedure, the KSW process serves as a guide to the rigorous formulation and solution of amenable problems, avoiding errors associated with interactions between partial solutions and the aggregation of results at intermediate steps.

Acknowledgments

The author wishes to acknowledge the contributions of Dr. Paul Deitz who, as a division chief of the U.S. Army Research Laboratory (ARL), fostered the kind of environment that nurtured the questioning of fundamental concepts and the free discussion of new ideas.

Thanks are also due to Drs. James Walbert and Michael Starks and Messrs. Rick Saucier and Harry Reed for their aid in clarifying the enclosed concepts and the presentation thereof.

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1. Introduction

In the late 1980s, Deitz [1,2] began referring to the "Four Spaces of Vulnerability" in which he specifically recognized four constructs.

Space 1: All combinations of specific warhead/target initial conditions

Space 2: Particular damage vectors

Space 3: Objective Measures-of-Performance

Space 4: Various Measures-of-Effectiveness

Relating a specific state in one space with the corresponding state in the subsequent space was said to be done by "operators", designated as $O_{1,2}$, $O_{2,3}$, and $O_{3,4}$. This construct became known as the Vulnerability/Lethality (V/L) Taxonomy.

Figure 1, with its original caption, is taken from BRL-MR-3880.[2]

Of particular importance was the identification of specifically defined, quantifiable, measurable states at each step in the process, shown by the specific points in the ovals in Figure 1. By this construction, Deitz was able to point out differences between analyses that carry multiple specific sets of outcomes, each following from a specific predecessor, through the whole analysis process versus single-pass analyses in which aggregated (*e.g.*, averaged) values were brought from one step to the next. In particular, he used this construct to underscore the dangers inherent in the use of aggregated values ("averaging too soon").

Subsequent to the seminal work of Deitz, Klopcic, Starks, and Walbert (KSW)[3] attempted to add mathematical rigor to the taxonomy, showing that "this taxonomy allows a rational scientific approach to the V/L analysis process." Among other refinements, KSW replaced the term "Space", which has a precise mathematical definition, with the term "Level".

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[1] P. Deitz and A. Ozolins, *Computer Simulations of the Abrams Live-Fire Field Testing*, BRL-MR-3755, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, May 1989

[2] P. Deitz, M. Starks, J. Smith, and A. Ozolins, *Current Simulation Methods in Military Systems Vulnerability Assessment*, BRL-MR-3880, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, November 1990

[3] J. T. Klopcic, M. W. Starks, and J. N. Walbert, *A Taxonomy for the Vulnerability/Lethality Analysis Process*, BRL-MR-3972, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, May 1992

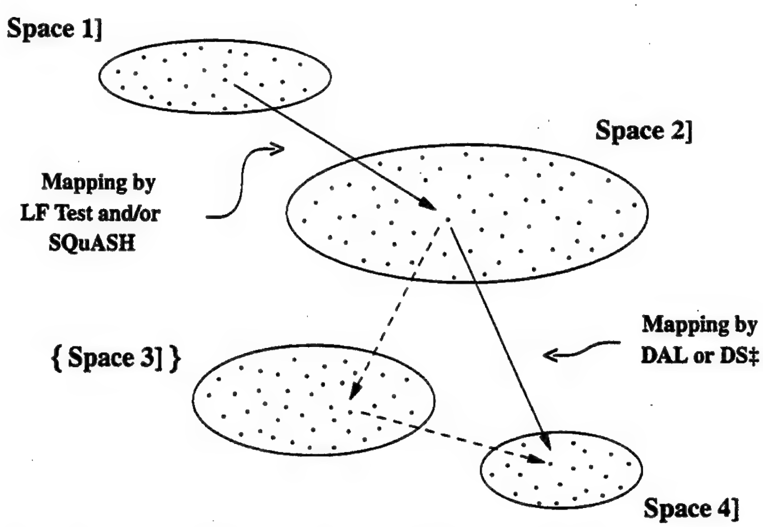

Figure 2.[□] Four Spaces of Vulnerability. Space 1] represents all combinations of specific warhead/target initial conditions. A given point represents one complete set of specifications. Individual points in Space 2] represent particular damage vectors, *i.e.* particular combinations of killed critical components, plus all post-shot damage observables such as armor exit holes, fragment effects, etc. The maximum size of the subset of Space 2] describing damage vectors is 2^n, where n is the number of critical components in the target. Space 3] represents objective Measures-of-Performance and is not modeled so the related mapping processes are indicated as dashed lines.[‡] Space 4] characterizes various Measures-of-Effectiveness; the mapping process for ground vehicles has historically been *via* the Damage Assessment List (DAL). In the future all mapping will be *via* the Degraded States (DS) methodology.

[□] From Paul H. Deitz, Michael W. Starks, Jill H. Smith and Aivars Ozolins, *Current Simulation Methods in Military Systems Vulnerability Assessment,* **Ballistic Research Laboratory Memorandum Report BRL-MR-3880,** November 1990.

[‡] This figure incorrectly categorizes the Degraded States (DS) mapping as a **Space 2]** to **Space 4]** transformation. In subsequent work the DS mapping has been recognized as a transformation from **Space 2]** to **Space 3]** (indicated by the upper dashed line). See Paul H. Deitz, *A V/L Taxonomy for Analyzing Ballistic Live-Fire Events,* **US Army Research Laboratory Technical Report ARL-TR-1274,** December 1996. To arrive finally at Measures-of-Effectiveness (Military Utility, *via* lower dashed line), a **Space 3]** to **Space 4]** operator must be invoked. See Paul H. Deitz and Michael W. Starks, *The Generation, Use, and Misuse of "PKs" in Vulnerability/Lethality Analyses,* **US Army Research Laboratory Technical Report ARL-TR-1640,** March 1998.

Figure 1: The Four Spaces of Vulnerability (with Original Caption)[2]

As enumerated by the above authors, there are three salient features of the process.

1. **MULTILEVEL:** A vulnerability analysis goes through three **essential** stages, called "Levels". These are:

   Level 1: Quantitative specification of the **initial configuration.**

   Level 2: The application of physics to reach a **resulting physical state.**

   Level 3: An engineering evaluation of the system in the resulting physical state, expressed as a (resulting) **system capability state.**

2. **MEASURABILITY:** Since we are addressing single events in which each event involves physical processes, the quantities evaluated at each level are inherently, directly measurable. That is, one can – at least in principle – measure the encounter conditions (Level 1), the results of any physical processes (Level 2), and the residual capability of the system (Level 3). Note that such would not be the case if a level were concerned with probabilistic quantities or quantities such as "usefulness" which require subjective evaluation.

3. **INTERFACING:** It is recognized that the need to interface with other users/applications requires two other steps (levels) that do not fit into the strict, measurable paradigm of Levels 1, 2, and 3. The taxonomy was therefore expanded to include a generally non-rigorous level which serves to represent the totality of input sources from which a measurable initial configuration is drawn. This level is referred to as Level 0. In addition, in order to interface with users of the results of an analysis, it might be necessary to aggregate results at Level 3, interpret Level 3 results, and/or combine Level 3 results with other information (such as scenario-dependent factors). The resulting outputs from such activities are said to be held in Level 4.

This process, as depicted by Reed, [4] is presented in Figure 2.

Subsequent to this work, a number of investigators, including the above authors, refined the concept of the V/L Taxonomy. Generally speaking, these refinements took one of two directions. A small amount of work was done,

[4] Harry L. Reed and J. Terrence Klopcic (editors), *Fundamentals of Vulnerability/Lethality Assessment. Book 1: Overview*, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, in publication

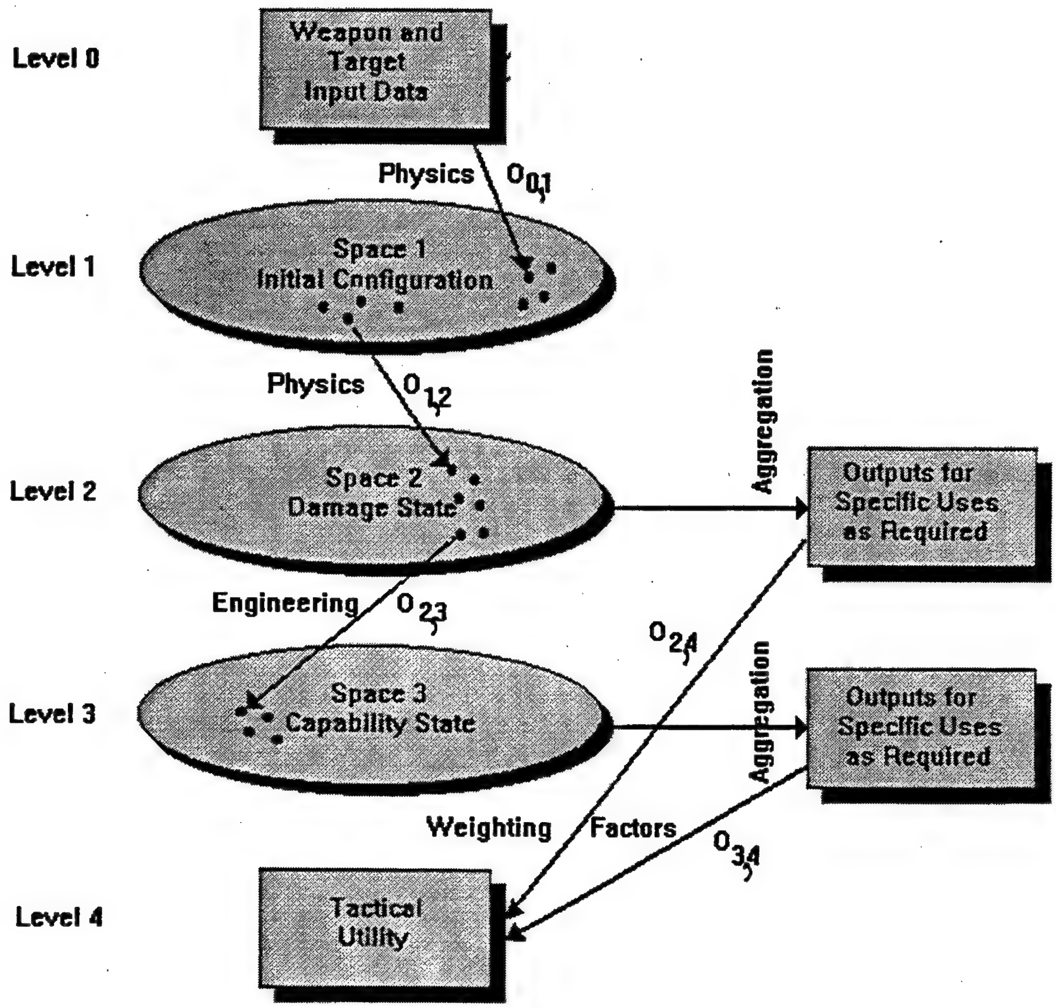

Figure 2: Taxonomy of the V/L Analysis Process

primarily by Walbert, to continue the attempts made by KSW to add rigor to the mathematics underlying the V/L Taxonomy and, by so doing, to enhance the power of the process by identifying the applicable tools from the mathematical disciplines. This work is referenced in Section 2.5.

Another, far more widely published avenue of subsequent development involved a particular way of expanding the taxonomy to other activities within the U.S. Army Research Laboratory, Survivability/Lethality Analysis Directorate (SLAD). These expansions generally began with an application of the existing taxonomy to a vulnerability/lethality analysis. In an attempt to show the broader applicability of the taxonomy, the expander then added levels, either backward (Level -1, Level -2, ...) to show the development of inputs leading to V/L analysis or forward (Level 5, Level 6, ...) to indicate application of results within an expanded taxonomy. In many cases, Levels 0 and 4 were redefined to conform to these expansions.[5,6,7]

Unfortunately, expansions of the latter type have served to obscure the underlying logic of the process. Rather than a general analytical procedure, the taxonomy thus used becomes a management tool, a means of diagramming data flow within a series of related projects. While certainly a worthwhile goal, it is clear that such use undermines the value of the taxonomy as an analytical tool: instead of being used to guide the specification of steps to be taken in an analysis, the taxonomy is merely used to record steps that were otherwise determined.

It is this essential difference, the use of the V/L Taxonomy as an analytical procedure, as opposed to a management tool, that is the subject of this report. It is the purpose of this report to revisit the concept of the KSW Process as a general analytical procedure and to restate its mathematical and applicational challenges.

In order to differentiate between the V/L Taxonomy as expanded programmatically and the analytical procedure that underlies the V/L Taxonomy as formulated by KSW, this report refers to the latter as the "KSW Process".

[5]Richard L. zum Brunnen, *Introducing Chemical/Biological Effects into the Ballistic Vulnerability/Lethality Taxonomy*, ARL-TR-715, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, March 1995

[6]Brian G. Ruth and Phillip J. Hanes, *A Time-discrete Vulnerability/Lethality (V/L) Process Structure*, ARL-TR-1222, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, November 1996

[7]William J. Hughes, "A Taxonomy for the Combined Arms Threat", *Chemical/Biological/Smoke Modeling and Simulation Newsletter, Vol.1, No.3*, published by the Chemical Biological Information Analysis Center, Fall 1995.

2. The KSW Process as a General Analytical Procedure

2.1. General Analytical Procedures

In order to reconsider the KSW Process as a general analytical procedure, it is useful to review the concept of such procedures.

In this report, the term "general analytical procedure" refers to an orderly, cogent series of actions or operations conducing to a selected end. Perhaps the best known example of a general analytical procedure is the specification known as "the Scientific Method". Although variously stated, the method consists of the following steps.

Step 1: Define the question as precisely and quantifiably as possible.

Step 2: Formulate an answer as a testable hypothesis.

Step 3: Plan and conduct research (*e.g.*, experiments) to gather data pertinent to testing the hypothesis.

Step 4: Analyze the results and draw conclusions on the validity of the hypothesized solution.

Reflection on the Scientific Method as a general analytical procedure brings the following observations.

a. It is applicable to a wide variety of problems. However, to be amenable to solution by the Scientific Method, a problem must have certain characteristics: most notably, a problem must have a solution that is testable.

b. The method is used to guide the problem-solver. It provides a check-list which the problem-solver uses to assure that his final conclusion will be acceptable.

c. The method remains unchanged, even if applied multiple times to a series of related or linked problems. In such multiple applications, the problem-solver precisely defines the various parts of the overall problem. Each part then becomes "the question" as specified in Step 1, above.

d. Use of the method by those who solve applicable problems becomes so routine and "second nature" that the method passes into the realm of "common sense" and practitioners cease to be aware that they are using it.

It is in this sense that this report considers the KSW Process to be a general analytical procedure. In the next section, the characteristics that make a problem amenable to solution by the process are discussed. In the following section, examples are presented that demonstrate the broad applicability of the process, including application to a linked example.

2.2. Indications for Applicability of the KSW Process

The characteristics of a problem amenable to solution by the KSW Process can be derived from the salient characteristics of the procedure as enumerated above, *viz:*

1. **MULTILEVEL:** The KSW Process presents a prescription for dealing with problems in which the final result is indirectly related to the initial conditions through one or more intermediate states. In the case of V/L analysis, the problem is usually to determine the loss of functionality of an attacked target. This is parsed into initial conditions leading to a damaged target (intermediate state), from which the loss of specific functionality is determined.

2. **MEASURABILITY:** The initial state, intermediate state, and resulting state must be expressible as measurable quantities. In V/L analyses for a penetrating munition, these quantities are the specifics of the initial state (such as penetrator and target, impact location, and penetrator kinematics), an enumeration of the damaged components with precise definition of "damage", and quantification of the final functionality (top speed, slew rates, ...) for Levels 1, 2, and 3, respectively.

3. **INTERFACING:** In order to apply the KSW Process, it is often necessary to extract and quantify a set (or sets) of specific initial conditions from descriptive data. In the V/L analyses above, the problem may have been stated as a hit by the penetrator at a location on the target determined by a probability distribution centered about the centroid of the presented area. From this distribution, it is necessary to select

specific samples, each of which becomes the specific hit point for a specific analysis. By drawing a sufficient number of samples via a technique that guarantees adequate representation of the distribution, the total (descriptive) problem can be analyzed via specific cases.

Similarly, the results actually required might be more intangible and/or descriptive in nature, necessitating the application of "softer" quantities to the specific, measurable results in Level 3. In V/L analyses, the traditional measures for ground vehicle vulnerability, $P_{Mobility}$ and $P_{Firepower}$, are actually utility indicators that contain not only the effect of an attack upon the capabilities of the target, but also a set of weighting factors that account for the seriousness of the loss and the probability of encountering a need for the missing capability.

Thus, to be appropriate for application of the KSW Process, a problem must be multilevel and quantifiable, with the possibility of non-specific initial conditions and the inclusion of soft factors in the final result.

2.3. A Nondestructive Example

All previously published applications of the KSW Process have dealt with *destructive* processes in which some kind of threat (penetrator, electromagnetic radiation, toxic chemical) impinges upon a target and causes damage which reduces the target's capabilities. In order to demonstrate the breadth of applicability of the general analytical procedure, a *constructive* example (contrived for simplicity) is presented.

Consider a municipality with responsibility for its infrastructure, in particular, local transportation support (roads, bridges, underwriting of public transportation, *etc.*). In a particular budget year, a certain amount of money will be allocated for transportation causing the decision makers to initiate a study to determine the optimum allocation of the money.

To determine the applicability of the KSW Process, we consider the criteria enumerated in the previous section.

1. **MULTILEVEL:** Funding results in specific acquisitions: roads, bridges, new buses, ... The desired functionality is the transportation of people, directly influenced by the acquisitions and thus indirectly influenced by the funding. That is, the problem can be parsed into the following levels.

Level 1: Specific potential spending plans

Level 2: Acquisitions that result from each spending plan

Level 3: Transportation of people in a system that includes the new acquisitions.

2. **MEASURABILITY:** Each of the above levels includes states that are quantifiable.

   Level 1: In terms of money

   Level 2: In terms of new assets

   Level 3: In terms of people-miles, commuter-minutes, ...

3. **INTERFACING:** The initial state – a (usually proposed) budget, a *status quo* for the existing transportation system, a history of past purchases, *etc.* – is generally nebulous. However, enough information must be gleaned from this "Level 0" starting point to formulate specific, quantitative spending plans.

   Similarly, the final result that is actually desired is probably not people-miles; being in a governmental organization, the decision makers are apt to be politicians whose desired final product is approval of the voters. Hence, in the final analysis, a relationship must be shown between the Level 3 results and popular satisfaction.

Thus, it appears that the problem as outlined above meets the criteria for application of the KSW Process. Figure 3 presents the problem in KSW terms.

Notional application of the KSW logic leads to the following prescription for analysis of the Transportation Fund Allocation problem.

1. Each spending plan must be quantitatively formulated with specific goals and allocated costs. Furthermore, each plan must be complete, *i.e.*, must account for the entire allocation.

2. Quantitative models must be applied to show the actual acquisitions to be realized for the funds specified in each spending plan. In this case, the models might be acquisition models which include risk probabilistically. If so, then the KSW Process provides that multiple sampling (Monte Carlo methods) must be applied to generate specific outcomes (*i.e.*, specific successful acquisitions) at Level 2.

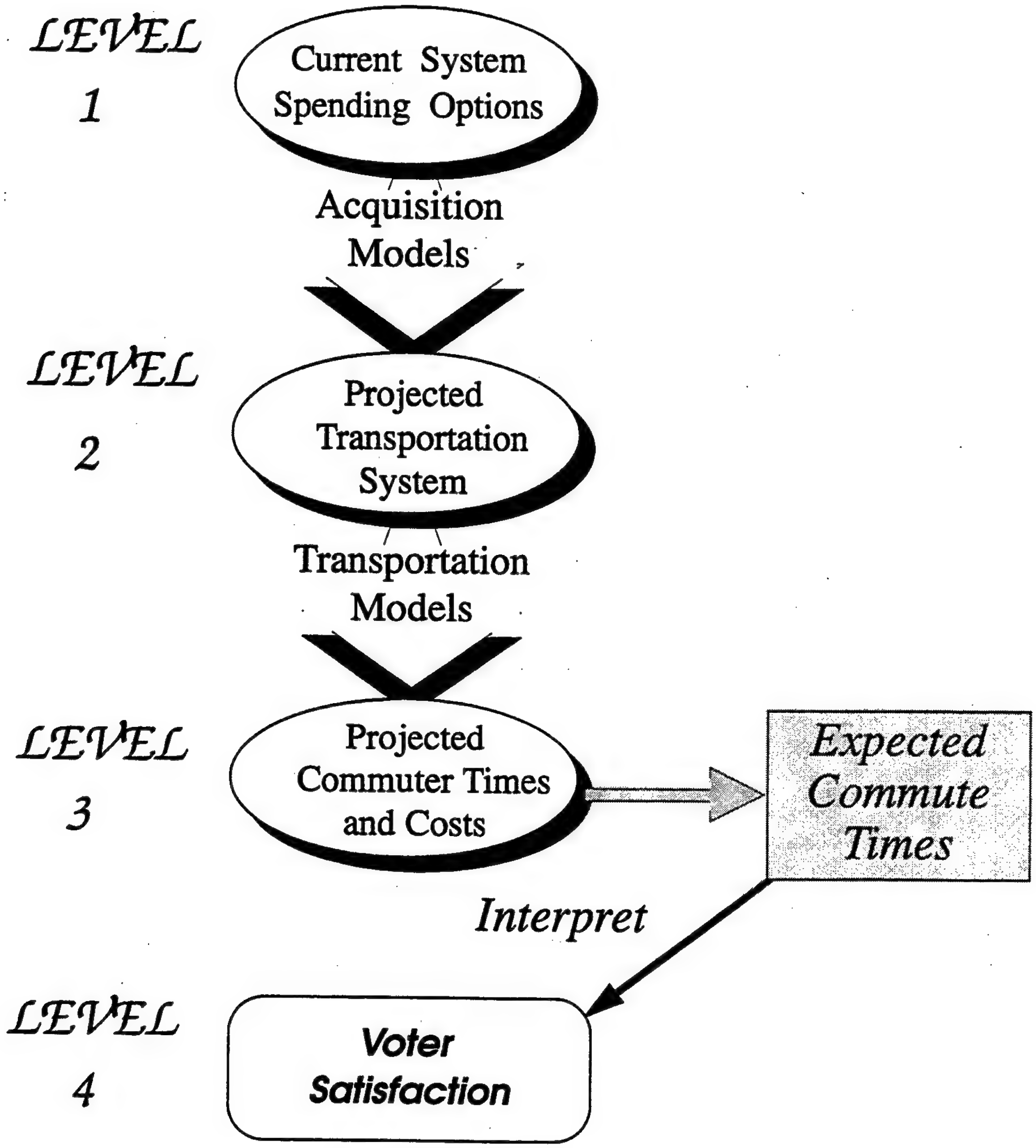

Figure 3: Application to Municipal Transportation

3. For each specific set of successful acquisitions generated at Level 2, transportation models must be applied to the entire system – existing assets plus new acquisitions – to generate people-moving (Level 3) results.

4. Detailed people-moving results can then be combined with other factors (politically favored communities, biases in the media, ...) to determine effective voter satisfaction.

Just as important as the above prescription for analytical steps to be performed are the proscriptions for steps *not* to take.

1. The KSW Process does not allow independent analysis of parts of a Level 1 set, thus assuring that interactions between all parts of every plan will be included in the subsequent analysis. In this case, this requirement forces the analysis to account for all required assets at the time each is required, for interference between parts of the plan, for bottlenecks resulting from multiple burdens upon any one part of the system, and for other such potentially deleterious interactions.

2. The inadmissibility of averaging too soon applies. The KSW Process does not allow the transportation analyst to run his/her probabilistic acquisition model several times, find an average set of acquisition times and costs, and then proceed to analyze that average set in his/her transportation model. To do so would miss foreseeing an unlikely but possible acquisition outcome that would result in unacceptably serious failures in the people-moving system.

3. Success must be defined at Level 4, which in this example was specified as a measure of voter satisfaction. Thus, although intermediate outputs may be of interest, success must be measured in terms of popular approval, not in terms of bridges built, buses bought, or people moved.

2.4. A Linked Example

Many applications of the V/L Taxonomy to linked problems have been presented in various fora. A representative example is the homing missile problem. In this problem, a jammer plays the role of the threat in the first part of the problem. As a result of the jammer, the miss distance distribution of the incoming missile is broadened. However, the missile warhead still functions, emitting blast and fragmentation that impinges upon the jammer-protected target.

As discussed above, in many cases, problems such as these were used to expand the V/L Taxonomy. In such expansions, the flight profile of the incoming missile became Level -2 and the status of the components of the missile post-jamming became Level -1. Level 0 was redefined to be the resulting broadened miss distance distribution, which fed into a conventional Level 1, 2, and 3 vulnerability analysis. Or, the expander might have labeled the incoming missile as Level -3, component upset as Level -2, miss distance as Level -1, and a fragment distribution as the redefined Level 0.

This example of expanding the V/L Taxonomy elucidates the statements made above: it is clear that the expander is not using the logic of the V/L Taxonomy as a guide. Rather, the expander has *a priori* decided how to conduct the analysis and is now redefining the V/L Taxonomy in order to report his/her decision.

In terms of the KSW Process, the homing missile problem is formulated as follows. As above, it is recognized that the problem is actually a set of linked problems, one feeding the other. It is also recognized that both problems – the effect of a jammer on an incoming missile and the effect of blast and fragmentation upon a defended asset – are amenable to solution via the KSW Process. We therefore proceed to analyze the missile-jammer problem with the general scenario serving as Level 0; the specifics of the jammer, missile, and flight profile(s) constituting the specific, quantifiable states at Level 1; the application of electromagnetic (EM) radiation and component response codes to generate specific, quantified missile states at Level 2; and the application of flight dynamics codes to generate specific deviated flight profiles and miss distances at Level 3.

At this point, we look to the subsequent vulnerability analysis as the "user" of the results of the jamming analysis. If the vulnerability analysis will support the high level of detail in Level 3 of the jamming analysis, we simply pass the results through. Notionally, Level 3 results pass unchanged into Level 4 (output), which pass into Level 0 and Level 1 of the ballistic vulnerability analysis. In this case, the vulnerability analysis must implement a point burst methodology that accepts specific external points for bursting munitions.

However, should the vulnerability analysis not support as much detail as contained in Level 3 of the jammer analysis, the KSW Process provides for aggregating Level 3 results, perhaps into probable miss distributions at Level 4. These distributions can then be used, along with other information at Level 0 of the subsequent vulnerability analysis, to generate specific, quantifiable initial states for Level 1.

The linked missile jamming-endgame analysis is shown in Figure 4.

The major difference in the two approaches is the role of the expanded V/L Taxonomy versus the KSW Process in guiding the analysis process. In the former, the expanding number of negative levels is done *a priori* and the levels applied to the V/L Taxonomy. In the latter, it is the KSW Process that is applied to the levels, guiding the formulation of specific, quantifiable states, prescribing the end-to-end analysis, and proscribing against the errors as described earlier in this report.

Finally, we point out that a rigorous definition of the process is essential if its power is to be enhanced by the application of mathematical tools, as discussed in the following section.

2.5. Mathematics of the KSW Process

As stated above, Walbert[8] has made some efforts to rigorously establish the mathematical behavior of the KSW Process. Most of this work has been directed at the mathematical nature of the spaces formed by the state vectors at Levels 1, 2, and 3. (Note the exclusion of Levels 0 and 4. As discussed above, the need for flexibility in initial presentation and final outputs outweighs the benefits of rigor at the extreme levels.)

For the purposes of this report, it is sufficient to summarize the results of Walbert. Briefly, Walbert has demonstrated that it is possible to define constructs within each of the vulnerability levels (v-spaces) such that the resulting ensemble meets the mathematical criteria for a space.

Of more importance, Walbert has demonstrated the possibility of defining *metrics* (intuitively thought of as "distances") within a v-space. This is the grail of mathematical research for the KSW Process, since the establishment of a suitable metric would allow rigorous, quantitative expression of "closeness": Were suitable metrics available, an analyst would be able to measure how "close" his/her result was to an experimental result or how the vulnerability of one target differs from another. (Currently, in order to compare the results of an analysis, the analyst is forced to aggregate those results to a single Level 4 number, thus suffering the near total loss of information.)

Unfortunately, as Walbert points out, although promising, his work falls short of finding "other, more powerful (in the sense of VL analysis) metrics which

[8]James N. Walbert, *The Mathematical Structure of the Vulnerability Spaces*, ARL-TR-634, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, November 1994

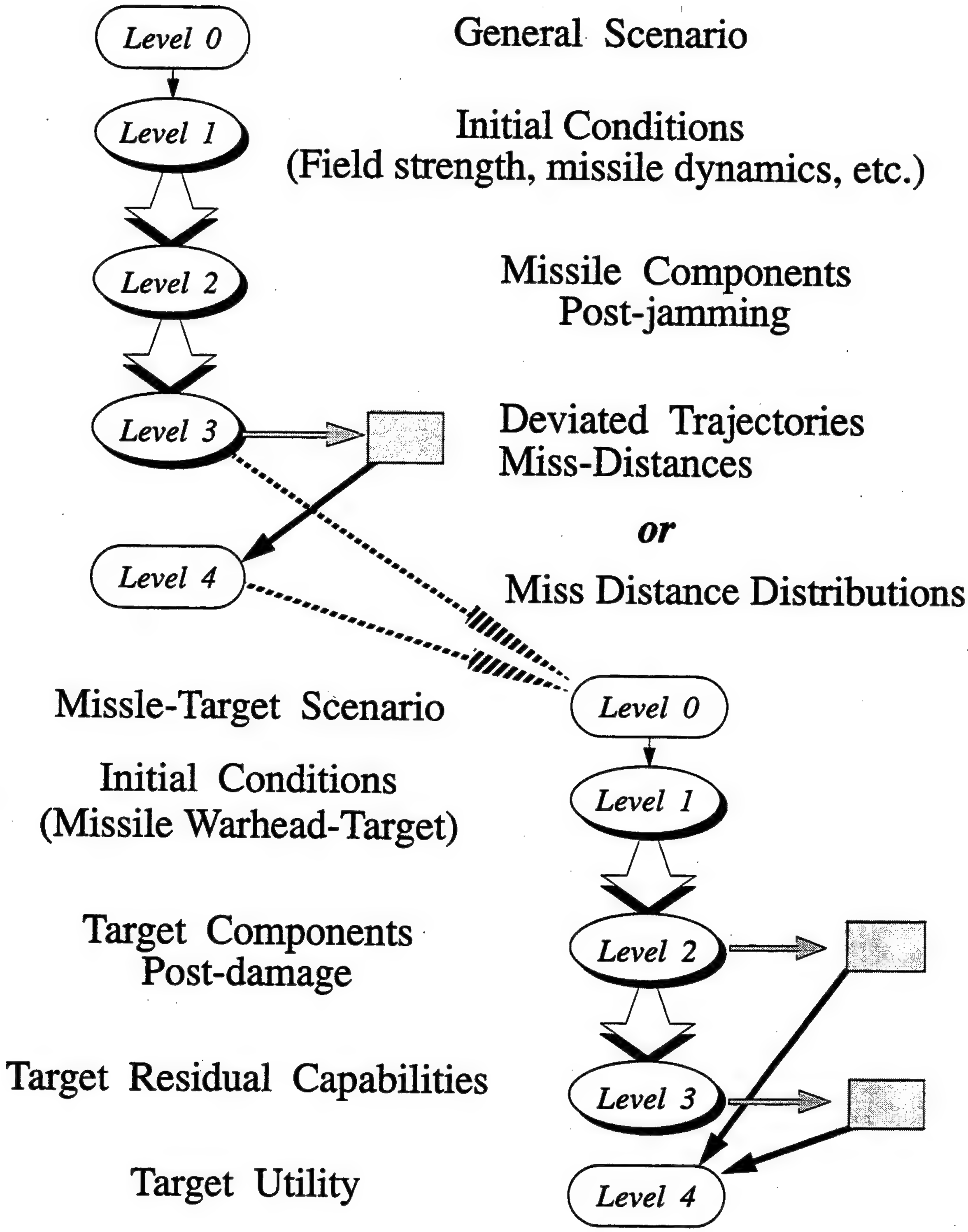

Figure 4: Linked Application to Missile Jamming - Endgame

could be defined on the spaces, providing insights into the solutions of other significant problems. Clearly, much remains to be done."

3. Summary

Many other taxonomic issues have been researched and reported elsewhere. Among these are the effects of granularity and the allowed applications of (usually aggregated) outputs from intermediate levels. The reader is directed to the material assembled by Reed.[4]

In this report, the V/L Taxonomy originally presented by Deitz and reformulated by Klopcic, Starks, and Walbert is shown to contain a general analytical procedure, herein referred to as the KSW Process, which is applicable to a broad class of problems that meet the criteria for its use. When used as a general analytical procedure, the KSW Process serves as a guide to the rigorous formulation and solution of amenable problems, avoiding errors associated with interactions between partial solutions and the aggregation of results at intermediate steps.

It is recognized that the logic contained in the KSW Process is neither novel nor unique to the vulnerability/lethality community. One notes, for example, that the proscription against the use of aggregated values at subsequent levels is a specific application of well-known mathematical theorems on the non-commutability of non-linear functions.

However, the KSW Process does serve the function of prescribing an approach to a broad set of actual problems in a form that is easily adapted by practitioners in various fields, particularly in the field of vulnerability/lethality analysis. The process avoids errors that can invalidate, sometimes very subtly, the results of analyses, particularly those errors that stem from "averaging too soon". It is for these reasons that the structure of the KSW Process should be preserved and its general applicability recognized.

[4]Harry L. Reed and J. Terrence Klopcic (editors), *Fundamentals of Vulnerability/Lethality Assessment. Book 1: Overview*, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, in publication

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13. ABSTRACT ***(Maximum 200 words)***

In this report, the vulnerability/lethality (V/L) taxonomy originally presented by Deitz and reformulated by Klopcic, Starks, and Walbert is shown to contain a general analytical procedure, herein referred to as the KSW process, which is applicable to a broad class of problems that meet the criteria for its use. When used as a general analytical procedure, the KSW process serves as a guide to the rigorous formulation and solution of amenable problems, avoiding errors associated with interactions between partial solutions and the aggregation of results at intermediate steps.

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